Appendix: An example of the analysis of a Wenner resistivity sounding (27 March 2020)

The program res1d provides an easy analysis of resistivity soundings that were measured with the Wenner or the offset Wenner array. This example of a simple Wenner sounding illustrates the steps of an analysis.

The measurements of resistance at the several electrode spacings can be converted to apparent resistivity with any spreadsheet program. The following data were analyzed:

S, m	R, ohm	P, ohm-m
0.1	171.5	107.70
0.2	56.2	70.59
0.3	20.8	39.19
0.4	8.76	22.01
0.5	5.82	18.27
0.7	3.21	14.11
1	2.10	13.19
1.5	2.56	24.12
2	1.70	21.35
3	1.52	28.64

where the numbers in the S column list the spacing between adjacent electrodes, R is the resistance that was measured, and P is the resistivity that was calculated from:

P = 2 * pi * S * R.

Prepare an input file for res1d

The spacing and resistivity values above are entered into a data file that will be read by the res1d program; this file states the array type (Wenner), the number of measurements (10), the measured parameter (Resistivity), and finally the measurements themselves, in two columns, as shown below:

```
----------  start of input file "Wsound.dat"
Wsound
Array Type (Wenner or Schlumberger)
Wenner                                  | Wenner array or configuration
Number of data points
10                                      | number of measurements below
Data Type (Resistivity, IP, or SIP)
Resistivity
Error in measurements included (Yes, No)    | needed
No
Electrode spacing, Apparent resistivity
0.1     107.702
0.2     70.5872
0.3     39.1872
0.4     22.00512
0.5     18.2748
0.7     14.11116
1       13.188
1.5     24.1152
2       21.352
3.03    28.6368
----------  end of input file "Wsound.dat"
```

The text and numbers between the pair of dashed lines are saved to Wsound.dat; the dat extension is necessary. The | symbols precede comments. The first line has the title of this analysis; it will be included on the graphs of the inversion. The two lines about "Error in measurements" must be included although this option is not in the program. There must be at least five measurements of resistivity for an analysis, but these measurements do not need to be in order of the electrode spacing. The value for the electrode spacing and the value for resistivity can be separated by one or more tabs, spaces, or a comma.

The format shown above for the input file is easy to apply and the numbers can be changed for other measurements. An even simpler format can be applied since only some of the lines of the input file are read by the program; the following input file provides the same analysis as the one above:

```
----------  start of input file "Wsound simple.dat"
Wsound
0
Wenner
0
10
0
Resistivity
0
0
0
0.1     107.702
0.2     70.5872
0.3     39.1872
0.4     22.00512
0.5     18.2748
0.7     14.11116
1       13.188
1.5     24.1152
2       21.352
3.03    28.6368
----------  end of input file "Wsound simple.dat"
```

The lines that have only the digit 0 are not read by the program; these lines are just counted.

Do a quick analysis

Start the program res1d. Version 1.00.09 Beta was applied to this example; it works fine with Windows 10. Click File and then "Read apparent resistivity input file"; select file "Wsound.dat". The file will be read; a summary will be displayed as Figure 1.

Do an initial analysis of the data: Click on Inversion then "Invert with user model". There will be a note that there is no initial model in the file; click OK and the program will then calculate one. A window will show a changing graph that reveals the progress of an initial inversion. This will end within about a second, and a multi-layer model will be displayed; see Figure 2. Each of the measurements is marked with a black plus symbol in the graph; the electrode spacing is indicated on the logarithmic axis at the bottom of the graph. The solid black curve is a calculated sounding; this line passes near each measurement point.

The calculation is for the resistivity model in Figure 2 that is displayed with purple rectangles. The height of each rectangle shows the resistivity of each layer. The width of each rectangle marks the depth to the top and bottom of each layer, using the logarithmic axis in

purple at the top of the graph. The change of scale between the lower axis (electrode spacing in black) and the upper axis (depth in purple) aids the comparison between the resistivity model and the curve of calculated resistivity. There is a minor error on the top axis; its values should be half of those on the bottom axis, and the purple number at the upper left should be 0.05, rather than 0.1 that is shown there. The depth of 0.1 is correct for the next (unlabeled) tick mark to the right.

The resistivity model of Figure 2 has been determined by the res1d program. The number of layers (purple rectangles) was automatically-selected to be about the same as the number of measurements. The thickness and resistivity of those layers were changed by the program until the calculated curve (black) was closest to the measurements (+).

Perhaps this analysis is all that is needed. Resistivity and depth can be read directly on the logarithmic axes, but they may also be listed by simply clicking on OK in the window shown in Figure 2. Click the next OK and see the listing of the parameters for the topmost nine resistivity layers; see Figure 3.

If you would prefer to have a file that lists the resistivity and depth of the model strata, a minor change is needed at the start of the analysis. After selecting Inversion, choose Automatic Inversion. You can probably accept the default file name (Wsound.INV). The program will then display the same graph as before, but it will be larger. You can open the file Wsound.INV in any text editor and find the best parameters for the resistivity model at the end of the file. This will also have the full ten layers of this model, rather than just the first nine. This file lists the thickness of each layer; add these to get the depth to the bottom of each layer. You may start with this "Automatic Inversion" option, rather than the "Invert with user model" option for any analysis; however, if you know that you want a resistivity model with only a few layers, the "Invert with user model" option may be somewhat faster.

Calculate a 3-layer model

The resistivity measurements of Wsound.dat show a simple change from high to low to high resistivity with increasing depth (or increasing electrode spacing). A resistivity model with just three layers may be adequate for approximating the measurements of the sounding; the simplicity of fewer layers may also help one's understanding. To create a good initial 3-layer model for this inversion, the thickness of a group of adjacent layers that are similar can be added and then combined with their average resistivity values. These can be entered into the program as shown in Figure 4. However, it is not necessary that the initial parameters of this 3-layer model be very accurate; the program will provide the accuracy. One can even set each initial resistivity to 50 ohm-m, and set the thickness of both layers at 0.5 m; a good model will still be calculated.

After these parameters have been added to the "Enter user model" window, click on OK. After two notices, save the new model, perhaps as file "Wsound 3-layer.INV". The new and simplified model will then be displayed as a graph. Read the end of the INV file to see the best parameters for this model and data (Layer 1 starts at the surface):

Layer	Resistivity	Thickness
1	122.03	0.151
2	9.04	0.633
3	47.80	

Where Layer 3 (on the bottom) has an infinite thickness.

Since no further iterations are probably needed, hit the Esc key, or click on OK or Cancel to return to the main window of the program. To print the graph of this 3-layer model, click on Print/Dump and then "Save screen as BMP file", which may be named "Wsound 3-layer.bmp". This is shown in Figure 5; many graphics programs will display this bitmap file.

As an estimate, the number of layers needed for a good resistivity model is greater than or equal to the number of smooth high and low oscillations or excursions on the plot of the sounding curve. Single measurements that differ from a smooth curve are likely errors, and perhaps these should be removed from the data. Some other differences between the measurements and calculations may be caused by lateral changes in resistivity; these may be minimized with an offset Wenner sounding.

Other options of the program

If a previously-calculated model should be viewed again, click on Display at the main menu of res1d; then click on "Display Inversion Results". A new window will open; at File, click on "Read resistivity inversion results file" and select a *.INV file. After some data about the selected file is shown, click on Display, and then "Display Model" to see the graph of measurements, calculations, and the resistivity model.

If a resistivity stratification is assumed, the apparent resistivity that should be measured with a sounding can be calculated; this is the Forward Model option of the program. The data files for specifying these calculations have an extension of MOD, and several examples are included with the program.

The res1d program can also analyze IP measurements.

While an initial model for a resistivity sounding can be entered with the input file for the program; it may be difficult to estimate this model before displaying the data; it is probably easiest to enter this model within the program, as described above with "Calculate a 3-layer model".

The inversion settings for the analysis of resistivity soundings can be modified in the "Change Settings" options for the program. These options are clearly described within the program, and it is likely that no changes will be needed.

The manual and example data files for res1d mention options that do not appear to be in the current version of the program; these include specifying the error of resistivity measurements, and holding some parameters constant during iteration. While the manual says that a few 0s should follow the resistivity data in the Wsound.dat file, none appear to be necessary; perhaps these 0s are needed if an initial model is entered.

The program has no option for testing the equivalence of different resistivity models. For the example here, the middle layer of the 3-layer model could be changed to be thinner and have a lower resistivity; however, the calculated curve would be almost the same as before.

```
Wsound
Wenner array
Number of datum points is 10
Data Type (Resistivity, IP, or SIP)
Resistivity data
Error in measurements not available.
No.   Spac.  App. Res.
 1     0.10   107.70
 2     0.20    70.59
 3     0.30    39.19
 4     0.40    22.01
 5     0.50    18.27
 6     0.70    14.11
 7     1.00    13.19
 8     1.50    24.12
 9     2.00    21.35
10      3.03    28.64

Reading of data file C:\Users\User\Desktop\20200323 res1d example\Wsound.dat completed.
```

Figure 1: After reading the measurements of file Wsound.dat. This display indicates that the file was read okay; the phrase "Error in measurements not available" is not a problem and will always be shown here. If there is a error in reading the data, it will be listed with part of this text. If an error is indicated, check the format of the *.dat file; in particular, make certain the the number of datum points to be read (on the third line here) is equal to or less than the actual number of readings in the file. At least five measurements must be entered.

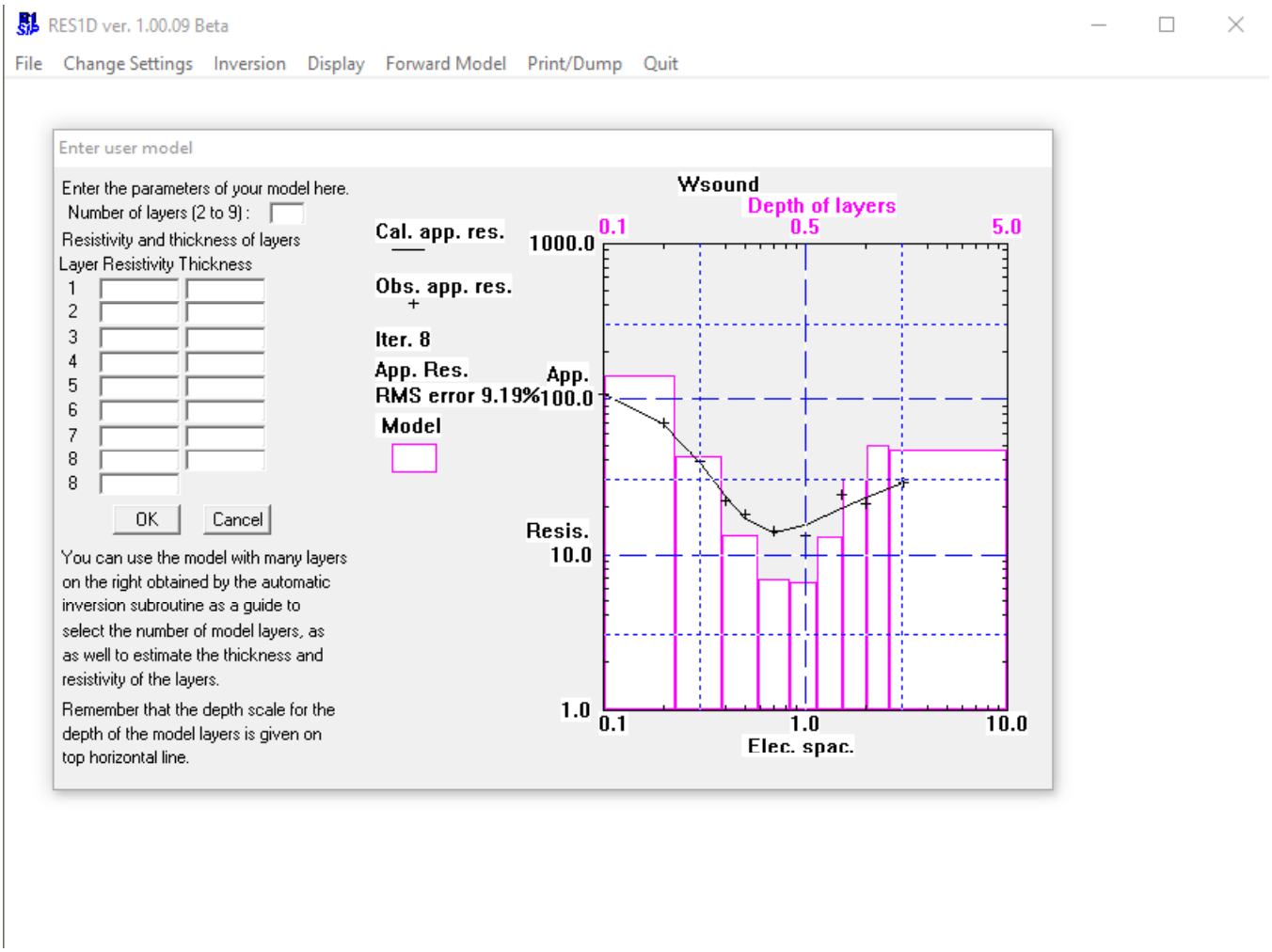

Figure 2: An initial look at the graph of the measurements. The main window of the res1d program is in the background. This display is shown after clicking on Inversion and then Invert with user model. The measurements that were made are plotted with plus symbols + here. The purple rectangles are an initial approximation of the resistivity stratification of the soil: Their top ends show the resistivity of each layer, while the sides show the depth to the top and bottom of each layer (using the scale at the top of the graph). Since this is a log-log plot, the width of the rectangles does not show the relative thickness of the layers. The calculated sounding is plotted as the smooth black curve; this passes close to the measurements, and this indicates that the resistivity model is a good approximation of the measurements.

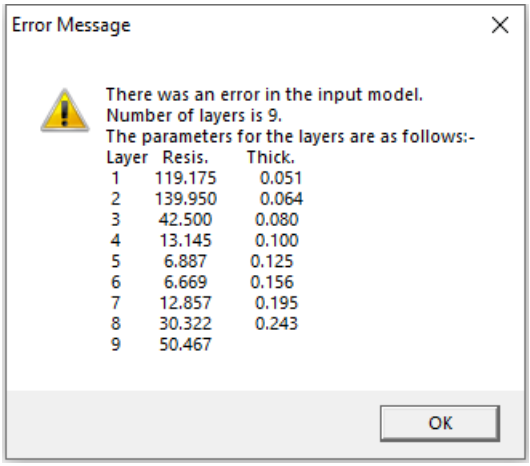

Figure 3: The resistivity and thickness of the layers. However, only the top-most nine layers are listed here, and the error message at the top can be ignored. However, this lists the actual thickness of the layers in the initial model, which has many layers. This display with its numerical values will be shown after clicking the mouse at OK in Figure 2. If the resistivity and thickness of all layers is wanted, it is only necessary to click on Inversion at the main window, and then Automatic Inversion; the parameters of the layers will then be listed at the end of the *.INV file that is generated.

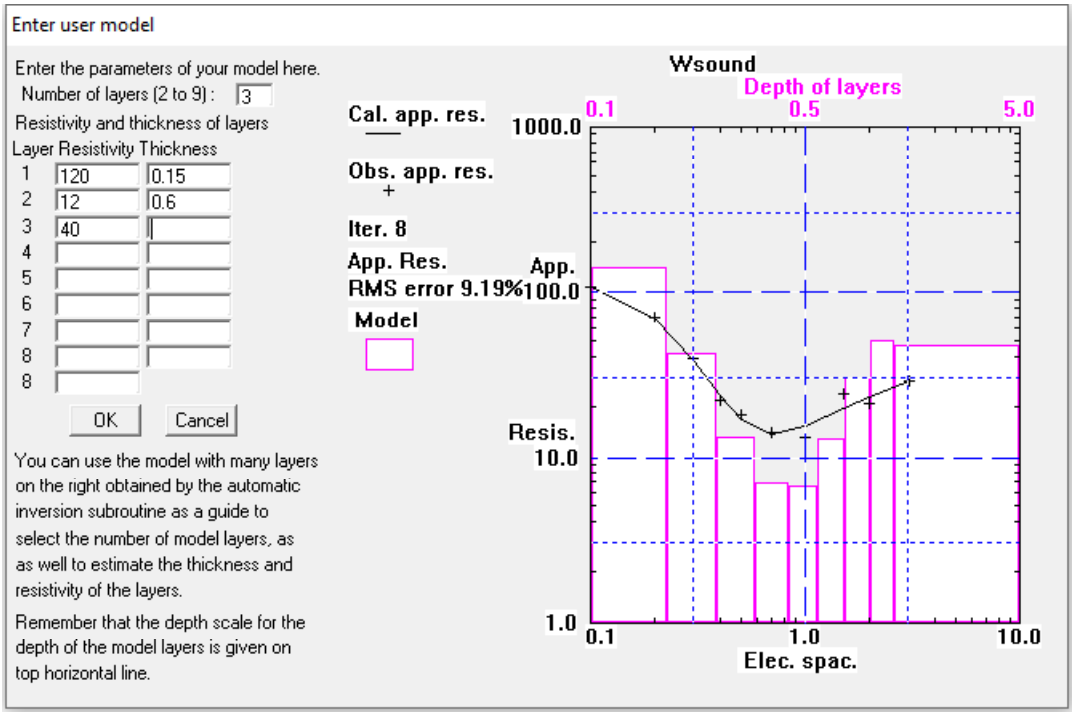

Figure 4: Starting a simpler model with only three layers. Some values have been entered into the table at the upper left. These list the number of layers or strata for the model and also a rough or initial estimate of the resistivity and thickness of those layers. Note that no thickness is entered for the bottom layer; it is assumed to be infinitely thick. While it is important to select the number of layers correctly, large differences in the initial parameters of resistivity and thickness will later result in almost the same resistivity model. To see that model, just click on the button OK or cancel, or press the Escape key.

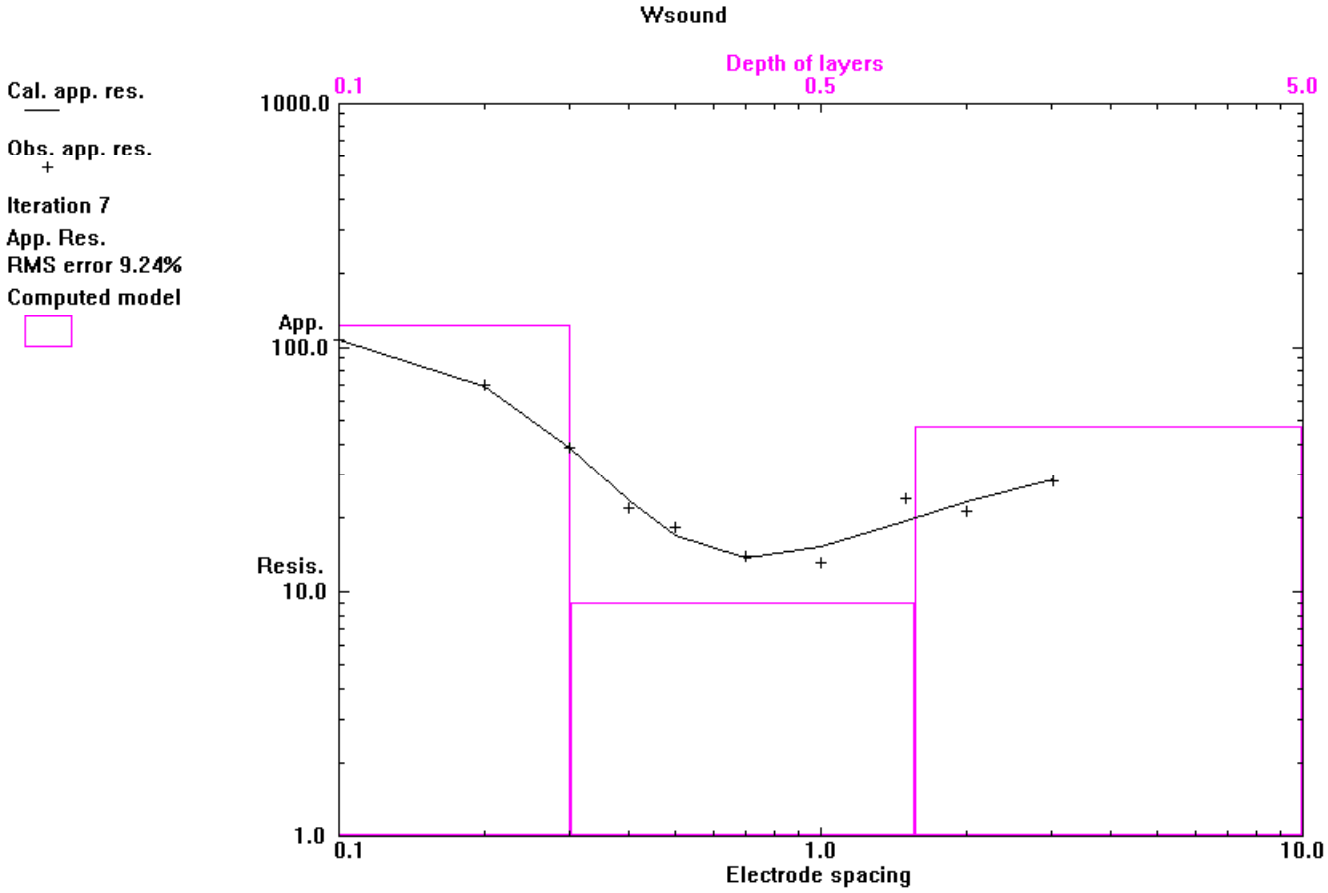

Figure 5: A good 3-layer resistivity model. With increasing depth, the resistivity of the layers is about 100, 10, and 30 ohm-m; the low resistivity middle layer extends between a depth of about 0.2 and 0.6 m. These parameters are listed more accurately at the end of the Wsound.INV file. While the actual soils at this location cannot be identified with this sounding, it is possible that the soil changes from loam to clay to silt with increasing depth.